

Role of nucleonic Fermi surface depletion in neutron star cooling

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(Dated: December 10, 2015)

The Fermi surface depletion of beta-stable nuclear matter is calculated to study its effects on several physical properties which determine the neutron star thermal evolution. The neutron and proton Z factors measuring the corresponding Fermi surface depletions, are calculated within the Brueckner-Hartree-Fock approach employing the AV18 two-body force supplemented by a microscopic three body force. Neutrino emissivity, heat capacity and, in particular, neutron 3PF_2 superfluidity turn out to be reduced, especially at high baryonic density, to such an extent that the cooling rates of young neutron stars are significantly slowed.

Key words: dense matter – stars: neutron – neutrinos

Online-only material: color figures

I. INTRODUCTION

Neutron stars (NSs), with typical masses $M \sim 1.4M_\odot$ and radii $R \sim 10\text{km}$, are natural laboratories for investigating exotic phenomena that lie outside the realm of terrestrial laboratories. They have been arousing tremendous interest since they are related to many branches of contemporary physics as well as astronomy (Haensel et al. 2006). In particular, NSs play the role of connecting nuclear physics with astrophysics, since they realize one of the densest forms of nuclear matter in the observable universe. Concerning NSs, important astrophysical quantities can be measured with increasing accuracy, such as mass, radius, surface temperature, spin period and spin-down, which provide valuable information and knowledge about these objects. On the theoretical side, much attention has been paid to the equation of state (EOS) of dense matter, including superfluid states, and cooling mechanisms via neutrino emission to understand the NS thermal evolution (Haensel et al. 2006).

Nowadays, the measurements on the NS surface temperature such as Cas A (Heinke & Ho 2010, Posselt et al. 2013), allow us to investigate the thermal evolution of NSs more deeply (Page et al. 2011; Shternin et al. 2011; Blaschke et al. 2012, 2013; Sedrakian 2013; Newton et al. 2013; Bonanno et al. 2014). Since the thermal evolution is quite sensitive to the equation of state (EoS) of NS matter, in particular to its composition and superfluidy states, one may grasp the crucial information and knowledge on the NS interior from this study. Thus, the exploration of the NS cooling might solve some difficult issues in nuclear physics, for instance, the density dependence of symmetry energy at supranuclear densities. The NS cools down via neutrino emission from the stellar interior in the first 10^5 years (Yakovlev & Pethick 2004), and several types of neutrino sources in the NS cores have been proposed as cooling mechanisms, such as the direct Urca (DU), modified Urca (MU) processes and nucleon-nucleon bremsstrahlung (see the review articles, Yakovlev et al. 1999, 2001; Page et al. 2004, 2006).

It has been stressed that the NS cooling relies on many factors (Yakovlev et al. 1999), including the neutrino emission mechanisms, heat capacity, thermal conductivity and reheating mechanisms in dense and superfluid states of matter. The latter has to be described as a quasi-degenerate Fermi system characterized by a large depletion of the Fermi surface due to the strong short-range correlations of nucleon-nucleon (NN) interaction (Migdal 1967). The Z -factor, that measures the deviation from a perfect Fermi gas described by the Fermi-Dirac distribution ($Z = 1$) can take values much less than one. This fact influences the level density of nucleons around the Fermi surface that controls many properties of fermion systems related to particle-hole

excitations around the Fermi energy. In our previous work, the Z factor effect on the 3PF_2 superfluidity of pure neutron matter was studied (Dong et al. 2013) and found that the gap was dramatically reduced. In this work, we generalize the previous approach to investigate the neutron 3PF_2 superfluidity of asymmetric nuclear matter and β -stable matter. The NS interior is assumed to be made of $npe\mu$ matter without exotic degrees of freedom. In such a context the Z factor effects on various neutrino processes and heat capacity, and on NS cooling are calculated. The material is organized as follows. In Sec. II, superfluidity, various neutrino processes and heat capacity affected by the Fermi surface depletion are respectively calculated and analyzed. Based on those results as inputs, the NS cooling is discussed in Sec. III. Finally a summary is given in Sec. IV.

II. QUASI-DEGENERATE NUCLEAR MATTER IN BETA-STABLE STATE: SUPERFLUIDITY, NEUTRINO EMISSIVITY AND HEAT CAPACITY

The deviation of a correlated Fermi system from the ideal degenerate Fermi gas is measured by the quasiparticle strength (Migdal 1967)

$$Z(k) = \left[1 - \frac{\partial \Sigma(k, \omega)}{\partial \omega} \right]_{\omega=\epsilon(k)}^{-1}, \quad (1)$$

where $\Sigma(k, \omega)$ is the self-energy as a function of momentum k and energy ω . According to the Migdal-Luttinger theorem (Migdal 1960), the Z factor at the Fermi surface equals the discontinuity of the occupation number at the Fermi surface. We calculated the Z factors in the framework of the Brueckner-Hartree-Fock (BHF) approach by employing the AV18 two-body force with a microscopic three body force (Li et al. 2008). The self-energy is truncated to the fourth order of the expansion in powers of G -matrix, namely, $\Sigma = \Sigma_1 + \Sigma_2 + \Sigma_3 + \Sigma_4$ (Jeukenne et al. 1976). Figure 1 displays, for the sake of illustration, the occupation probability of neutrons and protons in strongly asymmetric nuclear matter. The momentum distribution around the Fermi surface significantly departs from the typical profile of a degenerate Fermi system especially at high densities, which is attributed to the strong short-range correlations. In Figure 2, we show the Z factors at the Fermi surface Z_F calculated for nuclear matter in a β -stable state, suitable for application to NSs. The fraction of each component is determined by the EOS of nuclear matter from a BHF calculation.

In β -stable nuclear matter, the effect of the neutron-proton 3SD_1 coupling tensor channel (namely, $I = 0$ SD channel where I is the total isospin of two nucleons) of the nuclear interaction drives the deviation of neutron and proton Z -factors vs. total density. At very low density the system is mainly composed of neutrons and the neutron Z_F is that of a degenerate Fermi gas weakly interacting with few protons. On the contrary, the very diluted proton fraction is strongly interacting, via the $I = 0$ force, with large neutron excess, resulting into a strong depletion of the proton momentum distribution at low density. As the total density increases, also the proton fraction density increases for the competition with $I = 1$ force inducing an increasing Z_F value. Therefore, from the interplay between the two mechanisms the proton Z_F first increases and then decreases as shown in the figure. The calculated Z factor will be used in the following calculations.

A. Neutron 3PF_2 superfluidity

The superfluidity gap at the Fermi surface quenches all processes that involve elementary excitations around the Fermi surface, which could lead to an remarkable effect on the NS cooling. The 3PF_2 superfluidity in pure neutron matter has been investigated in a previous work with the inclusion of the Z factor (Dong et al. 2013). Here we generalized the investigation to isospin-

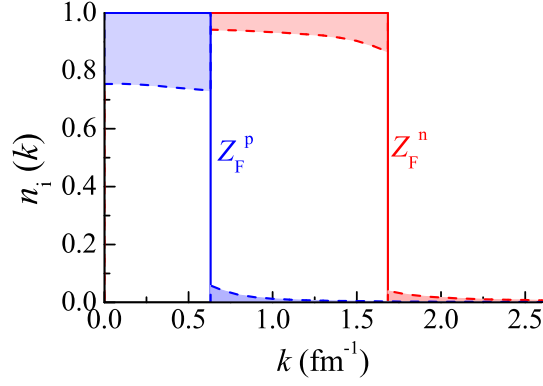


FIG. 1: Occupation probability of nucleons vs. momentum for asymmetric matter with isospin asymmetry $\beta = 0.9$ and density $\rho = 0.17 \text{ fm}^{-3}$. (A color version of this figure is available in the online journal.)

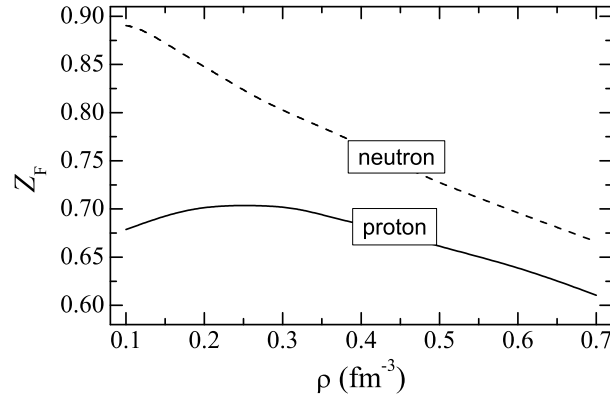


FIG. 2: Z factors vs density in β -stable matter. The fraction of each component is determined by symmetry energy from the BHF approximation.

asymmetric nuclear matter in β -stable condition. The 3PF_2 pairing gaps are determined by the following coupled equations

$$\begin{pmatrix} \Delta_L(k) \\ \Delta_{L+2}(k) \end{pmatrix} = -\frac{1}{\pi} \int_0^\infty k'^2 dk' \frac{Z(k)Z(k')}{E_{k'}} \times \begin{pmatrix} V_{L,L}(k, k') & V_{L,L+2}(k, k') \\ V_{L+2,L}(k, k') & V_{L+2,L+2}(k, k') \end{pmatrix} \begin{pmatrix} \Delta_L(k') \\ \Delta_{L+2}(k') \end{pmatrix}, \quad (2)$$

with $E_k = \sqrt{[\epsilon(k) - \mu]^2 + \Delta_k^2}$ and $\Delta = \sqrt{\Delta_L^2 + \Delta_{L+2}^2}$. $V_{L,L'}(k, k')$ is the matrix element of the realistic NN interaction including three-body forces. Here the angle-average approximation is adopted, and the relation between the gap at $T = 0$ and the critical temperature T_c is given by $k_B T_c = 0.57 \Delta(T = 0)$ (Baldo et al. 1992).

The calculated neutron 3PF_2 gaps for the β -stable matter are depicted in Figure 3, with $Z = 1$ (upper panel) and $Z \neq 1$ (lower panel). Similar to the case of the pure neutron matter (Dong et al. 2013), the Z factor effect quenches the peak value by about one order of magnitude, and it is extremely sizable at higher densities. Ding et al. (2015) calculated the influence of short-range correlations on the 3PF_2 pairing gap in pure neutron matter at high density with a different method, and also found that the gap is strongly suppressed. The peak value drops to 0.04 MeV and the superfluidity domain shrinks to $0.1 - 0.4 \text{ fm}^{-3}$. Such a weak superfluidity is not expected to explain the observed rapid cooling of NSs in the case of Cas A via the enhanced neutrino emission from the onset of the breaking and formation of neutron 3PF_2 Cooper pairs. Therefore, the role of the 3PF_2

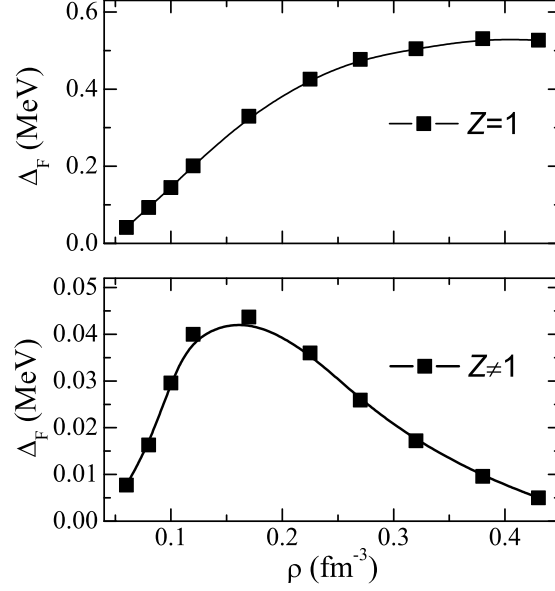


FIG. 3: Neutron 3PF_2 gap vs. total baryonic density in β -stable nuclear matter. The calculations with $Z = 1$ and $Z \neq 1$ are shown for comparison.

superfluidity in NS cooling is limited. The 3PF_2 pairing gaps do not change very much, even if the fraction of each component is controlled by a soft symmetry energy, such as in the case of APR EOS (Akmal et al. 1998).

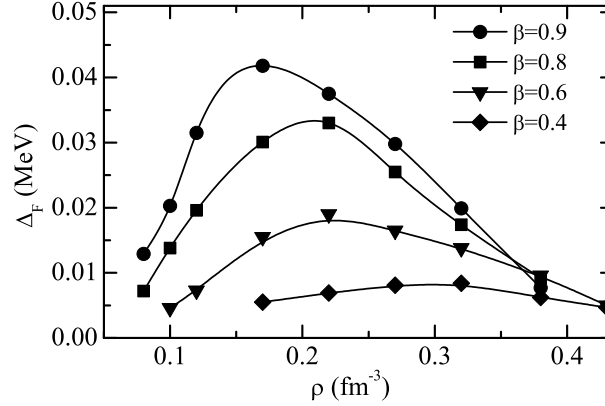


FIG. 4: Neutron 3PF_2 gap as a function of nucleonic density in asymmetric matter for various isospin asymmetries β .

To further explore the 3PF_2 superfluidity, the neutron gaps as a function of the total nucleonic density ρ for different isospin asymmetries β were calculated, and the results are shown in Figure 4. The isospin asymmetry is defined as $\beta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$, where ρ_n and ρ_p are the neutron and proton density, respectively. As β increases, the neutron density for a given total nucleonic density increases either. Accordingly, the peak value of the gap increases and their corresponding location shifts to lower density, that is primarily attributed to the decrease of the neutron Z factor for increasing β . Anyway, due to the departure of the system from the ideal degenerate limit, the neutron 3PF_2 gap is dramatically suppressed and the peak value is no more than 0.05 MeV.

For the nuclear matter with small isospin asymmetry, the gap may be vanishingly small. Therefore, in finite nuclei, the pairing comes from the 3PF_2 channel is completely negligible.

B. Neutrino emission

Since the deformation of the Fermi surface hinders particle-hole excitations around the Fermi level, the neutrino emission is accordingly expected to be depressed. To determine the neutrino emissivity, the key step is to derive the nucleon momentum distribution $n(k)$

$$n(k) = \int \frac{d\omega}{2\pi} S(k, \omega) f(\omega), \quad (3)$$

at finite temperature T and Z (Kadanoff & Baym 1962).

The spectral function $S(k, \omega)$ is a weighting function with total weight unity. $f(\omega) = 1/[1 + \exp(\frac{\omega - \mu}{T})]$ is Fermi distribution with temperature T and chemical potential μ . In the limit when k is extremely close to the Fermi momentum, the spectral function $S(k, \omega)$ can be expressed as

$$S(k, \omega) \approx Z(k) \delta(\omega - \omega_F), k \approx k_F \quad (4)$$

As a consequence, the momentum distribution function $n(k)$ of nucleon close to the Fermi surface is given as

$$n(k) = \frac{Z_F}{1 + \exp(\frac{\omega - \mu}{T})}, k \approx k_F. \quad (5)$$

The most efficient neutrino emission is provided by DU processes in the NS core

$$n \rightarrow p + l + \bar{\nu}_l, p + l \rightarrow n + \nu_l, \quad (6)$$

which correspond to neutron beta decay and proton electron capture, respectively. The DU process occurs only if the proton fraction is sufficiently high. We derive the neutrino emissivity $Q^{(D)}$ of the DU process under the beta-equilibrium condition with the inclusion of the Z factor. It is given by

$$Q^{(D)} = 2 \int \frac{d\mathbf{k}_n}{(2\pi)^3} \varepsilon_\nu dW_{i \rightarrow f} n_n(k) [n_p(k)|_{T=0} - n_p(k)] (1 - f_l), \quad (7)$$

where $dW_{i \rightarrow f}$ is the beta decay differential probability, $n_i(k)$ is the distribution function of nucleons including the Z factor, and f_l the Fermi-Dirac distribution function of leptons. Since the main contribution to this integral stems from the very narrow regions of momentum space close to the Fermi surface of each particle, the distribution function of Equation (5) can be employed here, and thus the above Equation (7) reduces to

$$\begin{aligned} Q^{(D)} &\approx 2 \int \frac{\varepsilon_\nu d\mathbf{k}_n}{(2\pi)^3} dW_{i \rightarrow f} \frac{Z_{F,n}}{1 + \exp(\frac{\omega_n - \mu_n}{T})} \frac{Z_{F,p}}{1 + \exp(\frac{-\omega + \mu_p}{T})} (1 - f_l) \\ &= 2Z_{F,n}Z_{F,p} \int \frac{d\mathbf{k}_n}{(2\pi)^3} \varepsilon_\nu dW_{i \rightarrow f} f_n (1 - f_p) (1 - f_l) \\ &= Z_{F,n}Z_{F,p} Q_0^{(D)}, \end{aligned} \quad (8)$$

where $Q_0^{(D)}$ is the neutrino emissivity of the DU process without introducing the Z factor, which has been well studied (see, e.g., the review papers, Yakovlev et al. 1999, 2001).

It is usually believed that one of the main neutrino energy loss processes in NSs are the MU process, which are several orders of magnitude less efficient than the DU processes. The MU processes differ from the direct one by a bystander nucleon required to allow momentum conservation

$$n + N \rightarrow p + N + l + \bar{\nu}_l, p + N + l \rightarrow n + N + \nu_l, \quad (9)$$

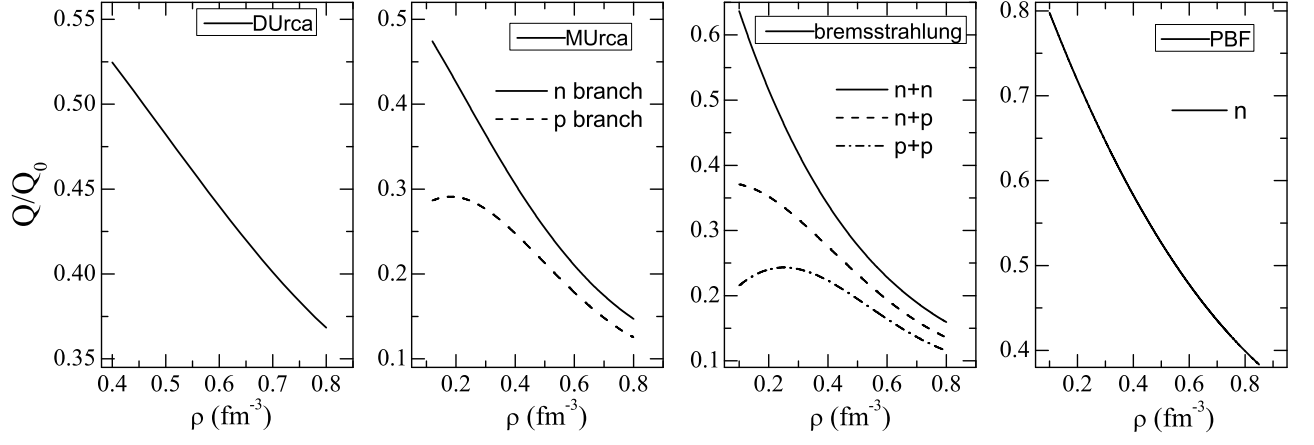


FIG. 5: Q/Q_0 for the DU, MU, nucleon-nucleon bremsstrahlung and PBF processes vs density ρ in β -stable NS matter. The fraction of each component is determined by symmetry energy from the Brueckner theory.

where N denotes neutron or proton. It is labeled by the superscript MN , where $N = n(p)$ denotes the neutron (proton) branch of the MU processes. Analogously to the procedure for the DU processes, we derive the neutrino emissivity under the condition of beta equilibrium

$$\begin{aligned} Q^{(Mn)} &= Z_{F,n}^3 Z_{F,p} Q_0^{(Mn)}, \\ Q^{(Mp)} &= Z_{F,n} Z_{F,p}^3 Q_0^{(Mp)}. \end{aligned} \quad (10)$$

The nucleon-nucleon bremsstrahlung process

$$N + N \rightarrow N + N + \nu + \bar{\nu}, \quad (11)$$

is another neutrino process based on neutral current that produces $\nu\bar{\nu}$ pairs to take away the neutron star thermal energy, but is much less efficient than the MU processes. The corresponding neutrino emissivities with the inclusion of the Z factor are

$$\begin{aligned} Q^{(nn)} &= Z_{F,n}^4 Q_0^{(nn)}, \\ Q^{(np)} &= Z_{F,n}^2 Z_{F,p}^2 Q_0^{(np)}, \\ Q^{(pp)} &= Z_{F,p}^4 Q_0^{(pp)}. \end{aligned} \quad (12)$$

The onset of pairing also opens a new channel of neutrino emission due to the continuous formation and breaking of Cooper pairs

$$N + N \rightarrow [NN] + \nu + \bar{\nu}, \quad (13)$$

that leads to energy release via $\nu\bar{\nu}$ emission, being analogous to the nucleon-nucleon bremsstrahlung process. It is very intense at temperatures slightly below the critical temperature T_c (Page et al. 2006, 2009), and it can be one order of magnitude more efficient than the pairing unsuppressed MU processes (Page et al. 2006). This Cooper pair breaking and formation (PBF) process due to neutron 3PF_2 pairing may be employed to explain the observed rapid cooling of the neutron star in Cas A (Page et al. 2011). With the inclusion of Z factor, the neutrino emissivity Q is given as

$$Q^{(PBF,n)} = Z_{F,n}^2 Q_0^{(PBF,n)}. \quad (14)$$

Figure 5 displays the calculated Q/Q_0 for the DU, MU, and bremsstrahlung processes as a function of density ρ . The DU process occurs just when the proton fraction exceeds a critical threshold, and the threshold relies on the density dependence of the symmetry energy at high densities. A stiff symmetry energy, such as that from the Brueckner theory, gives a low threshold. Frankfurt *et al.* (2008) showed that the modification of the nucleon momentum distribution due to the short-range correlations results in a significant enhancement of the neutrino emissivity of the DU process, and the DU process has a probability of being opened even for low proton fractions. However, our calculations reveal that the neutrino emissivity is reduced by more than $\simeq 50\%$, that is in complete contrast to their conclusion. We stress that, the short range correlations responsible of the Fermi surface depletion should be embodied in the quasiparticle properties, because the real system is actually a degenerate system of quasiparticles with the same Fermi momentum as the previous one. Therefore the kinematic conditions giving rise to threshold for DU process does not change. The beta decay of neutrons and its inverse reaction can be cyclically triggered just by thermal excitation, and thus $k \gg k_F$ and $k \ll k_F$ states do not participate into the DU process because the thermal energy $\sim k_B T$ is too low to excite those states. Accordingly, the occupation probability of proton hole for the thermal excitation, namely $[n_p(k)|_{T=0} - n_p(k)]$, should be employed in Equation (7), instead of $[1 - n_p(k)]$. The neutrino emissivity for the MU processes are reduced by $> 50\%$ for the neutron branch and $> 70\%$ for the proton branch. Because the proton Z factor is lower than the neutron one, as shown in Figure 2, the Q^{MN} of proton branch is more intensively depressed by the Fermi surface depletion. At high densities such as $\rho = 0.8 \text{ fm}^{-3}$, the Q^{MN} is reduced by one order of magnitude. Similarly, the nucleon-nucleon bremsstrahlung for $n-n$, $n-p$ and $p-p$ are reduced more distinctly at high densities. The computed Q/Q_0 for those processes do not rely on whether or not the superfluidity set on. The Q/Q_0 with a soft symmetry energy from APR (Akmal et al. 1998) does not provide very different results compared with those within BHF for the MU, nucleon-nucleon bremsstrahlung and PBF processes, but the threshold of the DU process is much larger due to the softer symmetry energy.

C. Heat capacity

The specific heat capacity of the stellar interior is the sum of the contributions of each fraction i (leptons and nucleons) (Page et al. 2004)

$$c_v = \sum_i c_{v,i}, \quad \text{with } c_{v,i} = \left(\frac{m_i^* p_{F,i}}{3\hbar^3} \right) k_B^2 T. \quad (15)$$

m_i^* and $p_{F,i}$ are effective mass and Fermi momentum of particle i . This equation is obtained under the assumption of non-correlated gas described by the Fermi-Dirac distribution. If the effect of the Fermi surface depletion is included, the specific heat of the nucleon i is given by

$$c_{v,i} = Z_{F,i} \left(\frac{m_i^* p_{F,i}}{3\hbar^3} \right) k_B^2 T, \quad i = n, p. \quad (16)$$

The heat capacity can be still altered by strong superfluidity.

III. NEUTRON STAR COOLING

To show the influence of the Z -factor induced reduction of the above three inputs afore discussed, namely, pairing gaps, neutrino emissivity and heat capacity, on NS cooling, we calculated the cooling curve for canonical neutron stars using the publicly available code NSCool^[1]. We employ the minimal cooling paradigm (Page et al. 2006) without fast neutrino emission,

[1] <http://www.astroscu.unam.mx/neutrones/home.html>

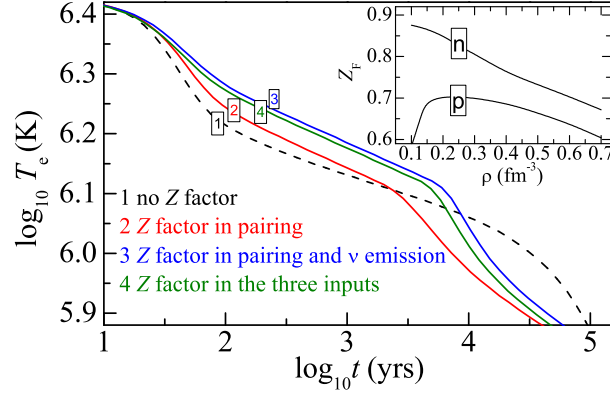


FIG. 6: Cooling curves of a canonical NS. The stellar structure is built with the APR EOS. The calculations without any Z factors, with Z factors only in superfluidity, with Z factors both in superfluidity and neutrino emission and with Z factors in the three inputs are shown for comparison. The inset shows the neutron and proton Z factors vs density in β -stable matter, the fraction of each component being determined by the APR EOS. (A color version of this figure is available in the online journal.)

with no charged meson condensate, no hyperons, no confinement quarks in canonical NSs. Therefore, we select the APR EOS and the above results as inputs, and the cooling curves are displayed in Figure 6.

The Z factor suppressing the neutron 3PF_2 superfluidity, retards the neutron star cooling for the first 3×10^3 years but accelerates the cooling thereafter. The critical temperature T_c for neutron 3PF_2 superfluidity is quite low as a result of the inclusion of Z factor. Therefore, the PBF cooling channel opens as soon as the stellar temperature falls below the T_c , which leads to a relatively fast cooling because it is more efficient than MU processes. The weak neutron 3PF_2 superfluidity, dramatically quenched by the Fermi surface depletion, cannot play a significant role in cooling of young NSs. The Z factor substantially reduces the neutrino emission of MU, nucleon-nucleon bremsstrahlung and PBF processes, and thus it slows down the thermal energy loss. Therefore, it significantly retards the cooling. The heat capacity of the neutron star is reduced by the Z factor, with the result that the thermal energy turns lower than in the case of excluding of the Z-factor effect. As a consequence, the NS cooling turns out to be enhanced, but this effect is not so sharp, as shown in Figure 6. It is well-known that the neutrino emission and heat capacity are sensitive to the superfluidity of stellar interior. However, due to the weak neutron 3PF_2 superfluidity reduced by the Z factor, neutrino emissivity and heat capacity cannot be suppressed. In a word, the effect of the Fermi surface depletion of nucleons on NS cooling cannot be neglected, when an accurate theoretical study of the cooling is performed, as in the case of the cooling of the NS remnant of Cas A.

IV. SUMMARY

We have investigated the superfluidity, neutrino emissivity for DU, MU, nucleon-nucleon bremsstrahlung and PBF processes and heat capacity, taking into account the Fermi surface depletion characterized by the Z factor. The Z factor is calculated in the framework of the BHF approach using the two body AV18 force plus a microscopic three body force. The superfluidity, neutrino emissivity and heat capacity are reduced by the Z factor, specially at high baryonic density. The effect of the Fermi surface depletion is needed to be included in a theoretically rigorous exploration of the NS thermal evolution, such as for the NS remnant in Cas A whose cooling rate was measured. Finally, based on the above results, we calculated the cooling curve for canonical NSs using the APR EOS, and we found that the Fermi surface depletion visibly affects the NS cooling.

Acknowledgement

This work was supported by the National Natural Science Foundation of China under Grants No. 11405223, No. 11175219, No. 11275271, No. 11435014 and No. 11175074, by the 973 Program of China under Grant No. 2013CB834405, by the Knowledge Innovation Project (KJCX2-EW-N01) of Chinese Academy of Sciences, by the Funds for Creative Research Groups of China under Grant No. 11321064, and by the Youth Innovation Promotion Association of Chinese Academy of Sciences.

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